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Higher-order results in the Higgs sector of the MSSM ‡

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We analyze the impact of the recent Feynman-diagrammatic (FD) two-loop results for the mass of the lightest $\mathcal{CP}$-even Higgs boson in the MSSM on the theoretical upper bound for m_{h} as a function of $\tan\beta$. The results are compared with previous results obtained by renormalization group (RG) methods. The incorporation of dominant FD two-loop corrections into the decay width $\Gamma(h \to f\bar{f})$ is also discussed.

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Abstract
We analyze the impact of the recent Feynman-diagrammatic (FD) two-loop results for the mass of the lightest $\mathcal{CP}$-even Higgs boson in the MSSM on the theoretical upper bound for $m_{\rm h}$ as a function of $\tan\beta$. The results are compared with previous results obtained by renormalization group (RG) methods. The incorporation of dominant FD two-loop corrections into the decay width $\Gamma(h \to f\bar{f})$ is also discussed.

1. Introduction

The lightest $\mathcal{CP}$-even Higgs boson in the Minimal Supersymmetric Standard Model (MSSM) is of particular interest, since it is bounded to be lighter than the Z boson at the tree level. The one-loop results [1–3] for its mass, $m_{\rm h}$, have in the last years been extended by the leading two-loop corrections, performed in the renormalization group (RG) approach [4], in the effective potential approach [5] and most recently in the Feynman-diagrammatic (FD) approach [6]. These calculations predict an upper bound on $m_{\rm h}$ of about $m_{\rm h} \lesssim 135$ GeV.

A precise prediction for the mass of the lightest $\mathcal{CP}$-even Higgs boson as well as for the cross sections of its production and decay processes is important for the Higgs-boson search at LEP2, the upgraded Tevatron and the LHC. If the lightest $\mathcal{CP}$-even Higgs boson will be found at the present or the next generation of colliders, its mass will be determined with a high precision, allowing thus a sensitive test of the model.

The dominant radiative corrections to $m_{\rm h}$ arise from the top and scalar top sector of the MSSM, with the input parameters $m_{\rm t}$, $M_{\rm SUSY}$ and $X_{\rm t}$. For simplicity, the soft SUSY breaking parameters in the diagonal entries of the scalar top mixing matrix are often assumed to be equal, $M_{\rm SUSY} = M_{\tilde{t}_L} = M_{\tilde{t}_R}$. The off-diagonal entry of the mixing matrix in our conventions (see Ref. [6]) reads $m_{\rm t} X_{\rm t} = m_{\rm t}(A_{\rm t} - \mu \cot\beta)$.

Up to now most phenomenological analyses have been based on the results obtained within the RG approach [4], where the neutral $\mathcal{CP}$-even Higgs-boson masses are calculated from the effective couplings in the Higgs potential. The results contain the leading logarithmic contributions at the two-loop level.

In the FD approach, on the other hand, the masses of the $\mathcal{CP}$-even Higgs bosons are obtained by evaluating loop corrections to the h, H and hH-mixing propagators and by determining the poles of the corresponding propagator matrix. In Ref. [6] the dominant two-loop contributions to the masses of the $\mathcal{CP}$-even Higgs bosons of $\mathcal{O}(\alpha\alpha_{\rm s})$ have been evaluated in the on-shell renormalization scheme. They have been combined with the complete one-loop on-shell result [3] and the sub-dominant two-loop corrections of $\mathcal{O}(G_\mu^2 m_{\rm t}^6)$ [4]. The corresponding results have been implemented into the Fortran code *FeynHiggs* [7].

In Ref. [8] the dominant contributions have been extracted from the full FD result. Taking into account the fact that the FD and the RG result have been obtained within different renormalization schemes and transforming the FD result of Ref. [8] into the $\overline{\rm MS}$ scheme, it has been shown that the RG and the FD approach agree in the leading logarithmic terms at the two-loop level [9]. The FD result, however, contains further genuine two-loop terms of non-logarithmic nature that go beyond the RG result. These genuine two-loop terms lead to an increase of the maximal value of $m_{\rm h}$ compared to the RG result of up to 5 GeV [9, 10].

2. Implications for $\tan\beta$ exclusion limits

By combining the theoretical result for the upper bound on $m_{\rm h}$ as a function of $\tan\beta$ in the MSSM with the informations from the direct search for the lightest Higgs boson, it is possible to derive constraints on $\tan\beta$. Since the predicted value of $m_{\rm h}$ depends sensitively on the precise numerical value of $m_{\rm t}$, it has become customary to discuss the constraints on $\tan\beta$ within a so-called "benchmark" scenario, in which $m_{\rm t}$ is kept fixed at the value $m_{\rm t} = 175$ GeV and in which furthermore a large value of $M_{\rm SUSY}$ is chosen, $M_{\rm SUSY} = 1$ TeV, giving rise to large values of $m_{\rm h}(\tan\beta)$.

In Ref. [11] it has recently been analyzed how the values chosen for the other SUSY parameters in the benchmark scenario (see Ref. [12] and references therein) should be modified in order to obtain the maximal values of $m_{\rm h}(\tan\beta)$ for given $m_{\rm t}$ and $M_{\rm SUSY}$. The maximal values for $m_{\rm h}$ as a function of $\tan\beta$ within this scenario ($m_{\rm h}^{\rm max}$ scenario) are higher by about 5 GeV than in the usual benchmark scenario. The constraints on $\tan\beta$ derived within the $m_{\rm h}^{\rm max}$ scenario are thus more conservative than the ones based on the previous benchmark scenario.

The $m_{\rm h}^{\rm max}$ scenario is defined as [11, 13]

$$
\begin{aligned}
& m_{\rm t} = m_{\rm t}^{\rm exp}\ (= 174.3\ {\rm GeV}),\ M_{\rm SUSY} = 1\ {\rm TeV} \\
& \mu = -200\ {\rm GeV},\ M_2 = 200\ {\rm GeV},\ M_{\rm A} \leq 1000\ {\rm GeV} \\
& X_{\rm t} = 2\, M_{\rm SUSY} \quad \text{(FD calculation)} \\
& X_{\rm t} = \sqrt{6}\, M_{\rm SUSY} \quad \text{(RG calculation)} \\
& m_{\tilde{\rm g}} = 0.8\, M_{\rm SUSY} \quad \text{(FD calculation)}, \qquad (1)
\end{aligned}
$$

where the parameters are chosen such that the chargino masses are beyond the reach of LEP2. In eq. (1) μ is the Higgs mixing parameter, M_2 denotes the soft SUSY breaking parameter in the gaugino sector, and $M_{\rm A}$ is the $\mathcal{CP}$-odd Higgs-boson mass.

Different values of $X_{\rm t}$ are specified in eq. (1) for the results of the FD and the RG calculation, since within the two approaches the maximal values for $m_{\rm h}$ are obtained for different values of $X_{\rm t}$. This fact is partly due to the different renormalization schemes used in the two approaches, i.e. the parameter $X_{\rm t}$ in the $\overline{\rm MS}$ scheme is shifted with respect to the corresponding parameter in the on-shell scheme [9, 10]. In *FeynHiggs* the gluino mass, $m_{\tilde{\rm g}}$, can be specified as a free input parameter. The effect of varying $m_{\tilde{\rm g}}$ on $m_{\rm h}$ is up to ± 2 GeV [6]. Within the RG result [4] used so far for the analysis of the benchmark scenario, $m_{\tilde{\rm g}}$ is fixed to $m_{\tilde{\rm g}} = M_{\rm SUSY}$. The corresponding values of $m_{\rm h}$ are about 0.5 GeV lower than the maximal values (obtained for $m_{\tilde{\rm g}} \approx 0.8\, M_{\rm SUSY}$).

While so far we have only been concerned with the definition of an appropriate scenario, we now turn to the impact of the new FD two-loop result for $m_{\rm h}$, which contains previously unknown non-logarithmic two-loop terms. Comparing the FD result (program *FeynHiggs*) with the RG result (program *subhpole*, based on the second and third reference of [4]) we find that the maximal value for $m_{\rm h}$ within the FD result is higher by up to 4 GeV.

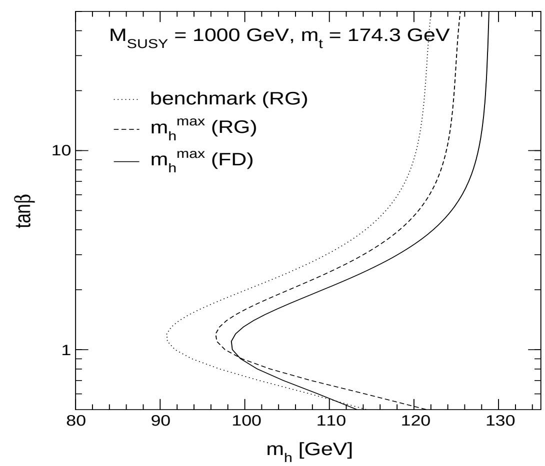

Figure 1. $m_{\rm h}$ is shown as a function of $\tan\beta$. The dashed curve displays the RG result within the benchmark scenario, while the dotted curve shows the RG result for the $m_{\rm h}^{\rm max}$ scenario (program *subhpole*). The solid curve corresponds to the FD result in the $m_{\rm h}^{\rm max}$ scenario (program *FeynHiggs*).

In Fig. 1 we show both the effect of modifying the previous benchmark scenario to the $m_{\rm h}^{\rm max}$ scenario and the impact of the new FD two-loop result on the prediction for $m_{\rm h}$. The Higgs-boson mass is plotted as a function of $\tan\beta$. The dashed curve displays the previous benchmark scenario, while the dotted curve shows the $m_{\rm h}^{\rm max}$ scenario. Both curves are based on the RG result (program *subhpole*). The full curve corresponds to the FD result (program *FeynHiggs*) in the $m_{\rm h}^{\rm max}$ scenario. The increase in the maximal value for $m_{\rm h}$ by about 4 GeV from the new FD result and by further 5 GeV if the benchmark scenario is replaced by the $m_{\rm h}^{\rm max}$ scenario has a significant effect on exclusion limits for $\tan\beta$ derived from the Higgs-boson search. Using the FD result for the $m_{\rm h}^{\rm max}$ scenario, an excluded $\tan\beta$ region appears only for an experimental bound on $m_{\rm h}$ of roughly 100 GeV, while in the previous benchmark definition values up to $\tan\beta = 2$ would already be excluded for a Higgs limit of about 100 GeV.

The constraints on $\tan\beta$ discussed above are of course only valid under the specific assumptions made in the considered scenario. In particular,

increasing m_t by one or even two standard deviations above the current experimental central value leads to a significant increase in the maximal value of $m_h(\tan\beta)$; increasing m_t by 1 GeV roughly translates into an upward shift of m_h^{max} of 1 GeV.

3. $\mathcal{O}(\alpha\alpha_s)$ Yukawa contributions to the decay width $\Gamma(h \to f\bar{f})$

As an extension of the FD two-loop results for the neutral $\mathcal{CP}$-even Higgs-boson masses, we consider now the leading two-loop Yukawa corrections of $\mathcal{O}(G_\mu \alpha_s m_t^4/M_W^2)$ to the decay width $\Gamma(h \to f\bar{f})$. These contributions enter the decay amplitude $A(h \to f\bar{f})$ in the following way,

$$A(h \to f\bar{f}) = \sqrt{Z_h}(\Gamma_h + Z_{hH}\Gamma_H). \qquad (2)$$

Γ_h, Γ_H are the $hf\bar{f}$ and $Hf\bar{f}$ vertex functions, and

$$Z_h = \left. \frac{1}{1 + \hat{\Sigma}'_h(q^2) - \left(\frac{\hat{\Sigma}^2_{hH}(q^2)}{q^2 - m^2_{H,(0)} + \hat{\Sigma}_H(q^2)}\right)'} \right|_{q^2 = m_h^2},$$

$$Z_{hH} = -\frac{\hat{\Sigma}_{hH}(m_h^2)}{m_h^2 - m^2_{H,(0)} + \hat{\Sigma}_H(m_h^2)}. \qquad (3)$$

Here $\hat{\Sigma}_h(q^2)$, $\hat{\Sigma}_{hH}(q^2)$, $\hat{\Sigma}_H(q^2)$ denote the real parts of the renormalized Higgs-boson self-energies and $m_{H,(0)}$ is the tree-level mass of the heavier $\mathcal{CP}$-even Higgs boson.

In Fig. 2 the results for the decay width $\Gamma(h \to b\bar{b})$ including the two-loop propagator corrections according to eqs. (2)–(3) are compared with the corresponding one-loop result for the cases of no mixing and maximal mixing in the scalar top sector. In both results the one-loop QED and QCD (gluon and gluino exchange) vertex corrections are included. The effect of the two-loop contributions is seen to be sizable. Since the branching ratio $\mathrm{BR}(h \to b\bar{b})$ is in general strongly dominated by $\Gamma(h \to b\bar{b})$, the correction to a large extent cancels out in the branching ratio. A comparison of our FD results with the corresponding results obtained within the RG approach is given in Ref. [14].

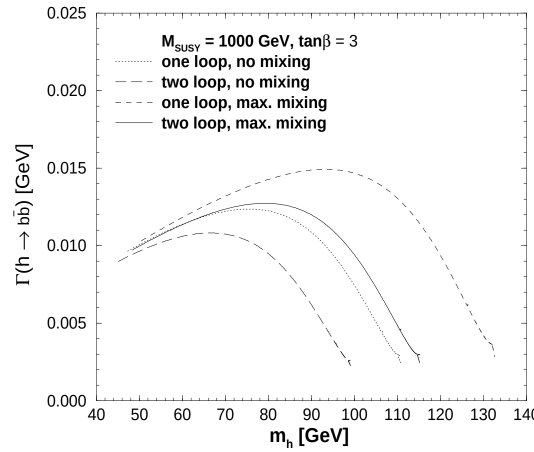

Figure 2. The results for $\Gamma(h \to b\bar{b})$ containing the Higgs propagator corrections at one- and two-loop order are shown as a function of m_h. The results are given in the no-mixing and maximal-mixing case for $\mu = -100$ GeV, $M_2 = M_{SUSY}$, $m_{\tilde{g}} = 500$ GeV, $A_b = A_t$.

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